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THE I/Q MODULATOR DESCRIBED

Digitalised image and sound signals have become an everyday occurence in the last decade. Polished algorithms for data reduction make it possible to transfer more and more information in a restricted frequency band, with or without a wire. Many digital modulation processes require a so-called I/Q modulator as key element. What this element does is to control a carrier frequency as regards phase and, if necessary, amplitude, with each carrier condition or each condition change represented by a bit sequence.

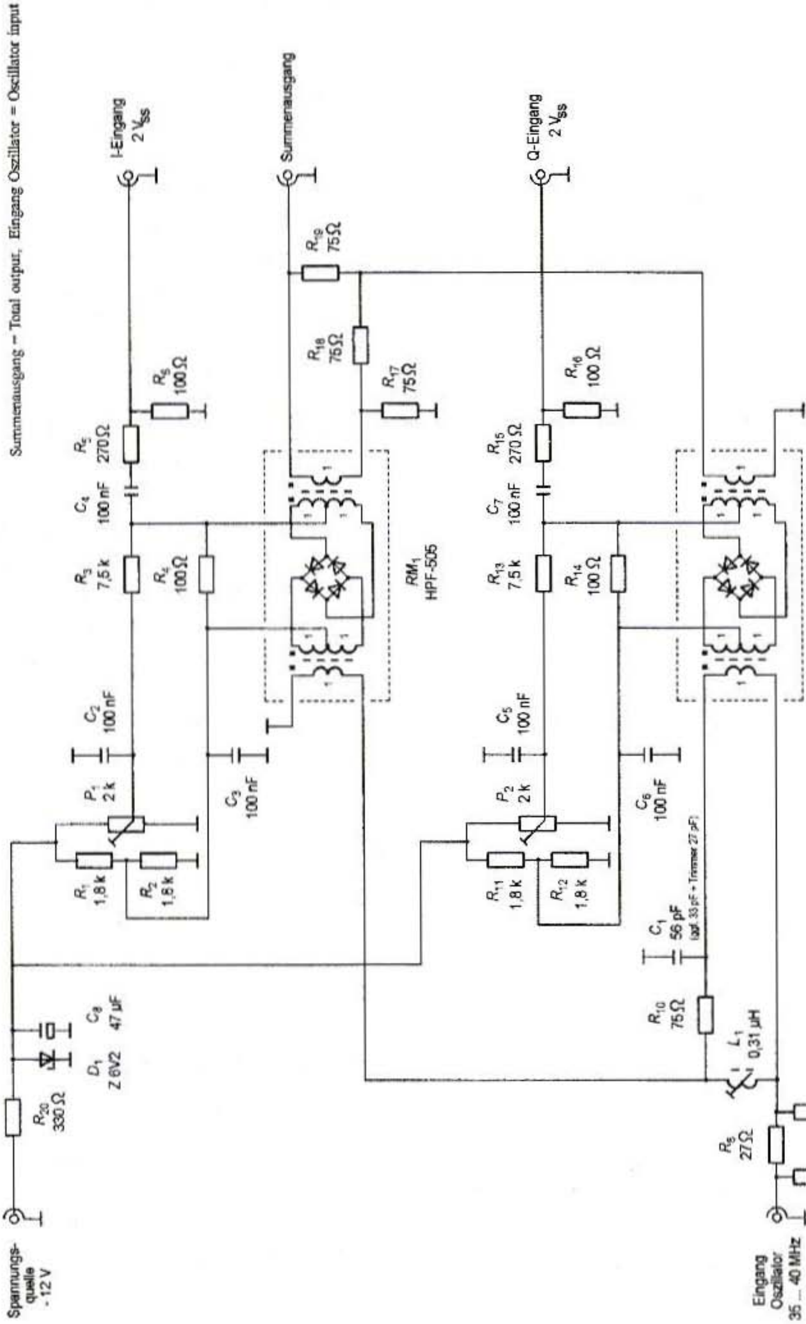
1. PRELIMINARY REMARKS

In principle, the I/Q modulator is fully digitalisable. Its output signal can be predicted, depending on the data to be transferred, and can be generated through D/A conversion. Its all a question of technology.

However, the I/Q modulator presented here stems from a time in which components were still wired. It operates as an analogue or a linear unit. The circuit, laid out using purely passive techniques, allows for an insight into what is going on. Various applications are discussed, starting from a basic circuit (Fig. 1), which can be easily built on the board shown in Figs. 2 and 3.

2. FROM DSB MODULATOR TO I/Q MODULATOR

By multiplying an oscillator signal (frequency: *f*o) with a modulation signal (frequency: *f*m), we obtain two new signals with the frequencies *f*o - *f*m and *f*o + *f*m. If a complete base band signal is multiplied by an oscillator signal - the modulation process two side bands are obtained (hence DSB, for double side band). If a DC voltage is applied to the multiplier, this means that the carrier (otherwise suppressed) appears in the spectrum.



Summenausgang = Total output, Eingang Oszillator = Oscillator input

Spannungsquelle = Voltage source, I-Eingang = I input, Q-Eingang = Q input

Fig. 1: Basic circuit of I/Q Modulator

In practise, multiplication is often carried out with the help of an electronic commutator switch (e.g. a diode ring mixer). The polarity of the modulation signal thus changes within the oscillator frequency cycle. Additional products are generated by means of this process, as well as the modulation products referred to above. They are grouped around the odd-numbered harmonics of the oscillator frequency and must be eliminated through filtration.

In comparison to the base band, the DSB signal takes up double the band width. But since frequencies are always scarce, it would be nice if we could double the use of the doubled band width. It is actually possible to separate two DSB signals again on the reception side, insofar as they have been generated with the same oscillator frequency and with a defined oscillator phase. In the ideal case, this gives us two transmission channels independent of each other.

From the mathematical point of view, the I/Q modulator consists of two multipliers which contain the modulation signals (I(t) and Q(t)). There is 90° difference between the oscillator signals. By convention the leading oscillator signal is applied to the multiplier in the Q path. If we look at the I oscillator signal as a reference, then the Q oscillator signal is displaced by a quarter-period to the left on the time axis. In the vector representation, is rotated 90° anti-clockwise

The output signals from the multipliers are added and then transmitted. Fig. 4 shows the interaction of modulator and demodulator, on the assumption that the multipliers have orthogonal phases in the I and Q channels, and that the transmission signal causes no signal delay (direct connection). It can be seen from the drawing that if the receiver oscillator is running synchronously with the transmitter oscillator ($\phi = 0$), we get back I(t) and Q(t) through synchronous rectification and subsequent low-pass filtration (provided with a system-dependent proportionality factor).

There are four conditions altogether free from cross-talk, namely ϕ = 0°, 90°, 180° and 270°. So at the demodulator outputs there is either the original, a transposition with I inversion, a two-sided inversion, or a transposition with Q inversion. Mind you, the phase position must be kept to very precisely with respect to channel separation (e.g. = 1° already causes a 35 dB cross-talk). Moreover, any deviation from the required orthogonality brings problems with it. Modulator errors and demodulator errors can compensate for each other or be cumulative, which makes this area very undefined. If we assume that we have an orthogonal demodulator, a 1° modulator error causes a channel cross-talk of 35 to 41 dB.

3. COMPLEX MODULATION

We are now making the assumption that the two modulation signals, I(t) and Q(t), receive discrete amplitudes (n different values, multi-valent data transfer), and that the change from one value to the other takes place at fixed times. It is best if we represent this in vector

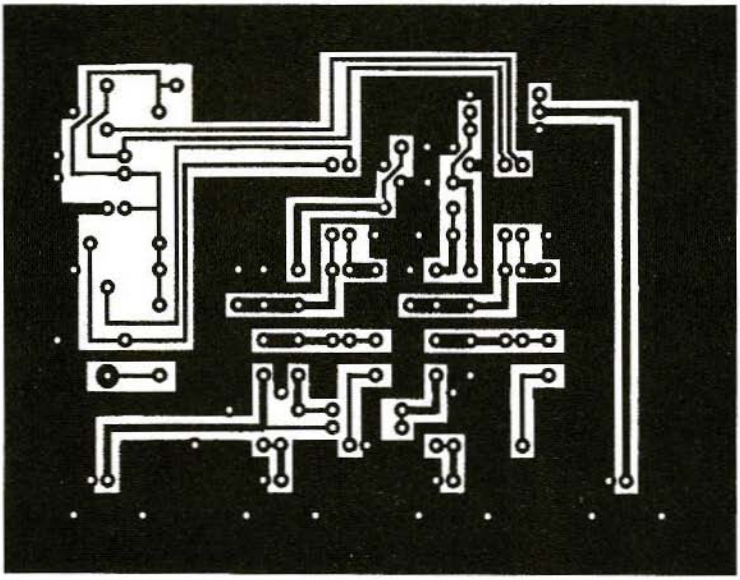


Fig. 2: Layout of I/Q modulator experimental printed circuit board

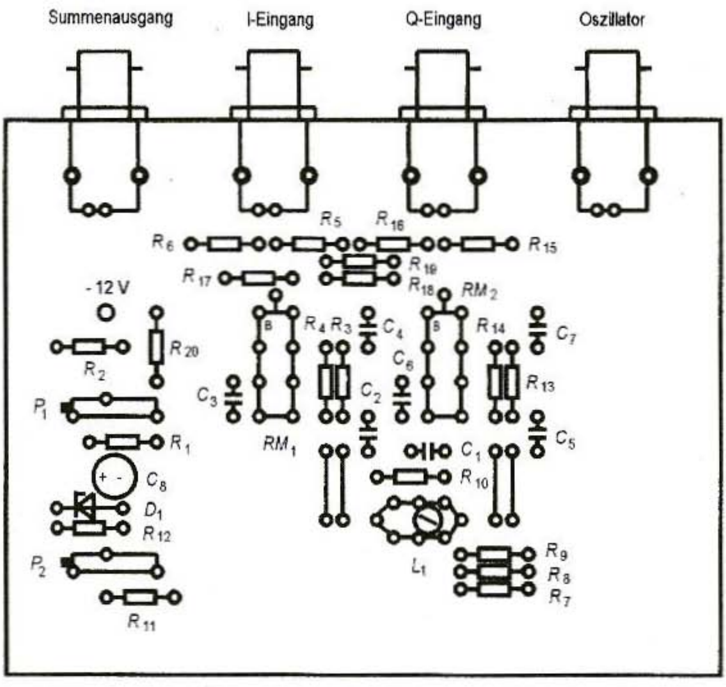


Fig. 3: Component plan of experimental printed circuit board

Summenausgang = Total output, I-Eingang = I input, Q-Eingang = Q input, Ozillator = Oscillator

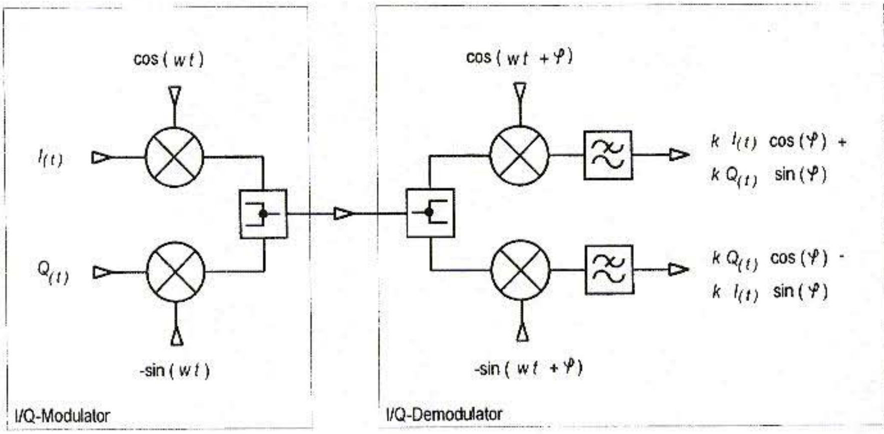


Fig. 4: Interaction of I/Q modulator and I/Q demodulator

terms. The I signal is plotted on the x axis and the Q signal on the y axis. Each I-Q combination corresponds to a reading with a defined amplitude and phase (an oscilloscope can make that very clear in x-y representation).

One known representative of the complex modulation procedures is, for example, QAM (quadrature amplitude modulation). QAM is distinguished by equidistant amplitude values in the I and Q channels. All possible pairings are also allowed. With four different values per channel (e.g. 1 V, - 0.33 V, + 0.33 V, + 1 V), we have 16-QAM, for there are 16 different combinations.

Also frequently encountered is PSK (phase shift keying). PSK sets the amplitude values in the I and Q channels in such a way that the total vectors always lie on a circle. With five different values per channel (e.g. 1 V, - 0.71 V, 0 V, + 0.71 V, + 1 V), we are dealing with 8-PSK, for we can then represent eight phase-differentiated readings with the same length (only specified I-Q combinations are permitted here).

If any reading ($\underline{Z}s = I(t) + jQ(t)$) is sent over the transmission system, in accordance with Fig. 4, the corresponding combination of the demodulator outputs gives

$$\underline{Z}E = k\underline{Z}se^{-j\phi}$$

In plain English, the reading received corresponds to the reading transmitted, but its phase angle is rotated through ϕ in a clockwise direction. If ϕ is sufficiently stable, the information transmission could take place in such a form that readings following each other in a

temporal sequence were compared with one another. It is advantageous if the carrier recovery circuit provides for ϕ = 0°, 90°, 180° or 270° (a Costas loop can do this), for then the amplitudes at the demodulator outputs take on only the pre-specified discrete values (no channel cross-talk), and can consequently be recognised using window comparator circuits without interference. It would be even better if there were only one scanning point, but the Costas loop does not cater for this. The uncertainty remains as to which quadrant we are in. Codewords can be agreed, or the difference can be evaluated for phase angles following one another.

Understandably, people try to transmit as much information as possible per unit of time. The finer the *I-Q* amplitude sub-division is, the more data can be transmitted for a given bandwidth. But then a good signal/noise ratio is required, with linear behaviour from the components taking part in the transmission. We can allow ourselves 64-QAM in the cable television systems. In satellite technology, we do not wish to differentiate amplitudes from one another. We rely on robust 4-QAM = 4-PSK, through which we can obtain a high degree of efficiency for the transmitter high-level stage (constant level control).

4. AN I/Q MODULATOR IN A PRACTICAL FORMAT

Following this theoretical introduction, let us now consider an I/Q modulator in practise. The circuit can easily be fitted onto half a European standard size pc board. This is certainly very large by todays industrial standards, but against this we can get by with standard commercial components. Fig. 2 shows the layout (solder side) and Fig. 3 the components plan for the I/Q modulator experimental printed circuit board. The top face of the 1.5-mm. epoxy printed circuit board is not etched so that all earth connections can be through-hole plated. The remaining bores are countersunk. BNC angle sockets form the interfaces to the outside world.

The heart of the circuit consists of two 7-dBm Schottky diode ring mixers (*RM*1, *RM*2). It is important that all mixer connections are accessible and not connected to earth at the manufacturing stage. Each mixer port is separated from the external inputs and outputs by means of additional attenuation. The system characteristic impedance is 75 Ohms.

The oscillator frequency should lie in the range between 35 and 40 MHz. An external generator supplies the oscillator signal (13 dBm). A 3-dB attenuator (*R*7, *R*8, *R*9) is followed by a 3-dB 90° distributor, de-coupled at the outputs, in a bridge circuit (*R*10, *L*1, *C*1). One of the distributor outputs must be tapped off potential-free, which is provided for by the transformer integrated in *RM*2. The ring mixers thus each have an oscillator level of 7 dBm (*RM*2 receives a signal running 90° ahead of *RM*1), so that they see a broad-band matching, and are de-coupled from one another.

The reactive impedances of *L*1 and *C*1, together with the resistance *R*10, must correspond to the system characteristic

impedance. Moreover, the source (oscillator) must be broad-band matched. $L1$ takes the form of a balancable inductance (11 turns of enamelled copper wire on a 4-mm. rod, ferrite core). $C1$ should likewise be balancable, if applicable (trimmer). The criterion for the correct values of $L1$ and $C1$ is a sharp form of reflection attenuation at the distributor input at the desired oscillator frequency (Fig. 5), with the minimum being of no interest as an actual reading (because of the final directivity of the measurement system) but being of interest only for reasons of reproducibility.

The mixers output signals are combined by a bridge circuit ($R17$, $R18$, $R19$). In this connection, an attenuation of 6 dB arises in each case. One of the coupler inputs must be switched potential-free, which is provided for by the transformer integrated into $RM1$. The condition for the de-coupling is that $R17$, $R18$ and $R19$ correspond to the system characteristic impedance, and in addition the sink (total output) must be broad-band matched.

A stabilised DC circuit of approximately 6 V is obtained from the voltage fed in from outside, using $R20$, $D1$ and $C8$. A DC voltage adjustable within a range of 0 mV to ± 20 mV is applied at the mixer inputs through the network consisting of $R1$, $R2$, $R3$ and $P1$ (or $R11$, $R12$, $R13$ and $P2$). $P1$ and $P2$ take the form of 10-turn helical potentiometers. We can thus generate components of the carrier frequency orthogonal to one another at the total output, each with up to approximately 30 dBm. Without DC voltage compensation (0 mV at the mixer inputs), the carrier frequency

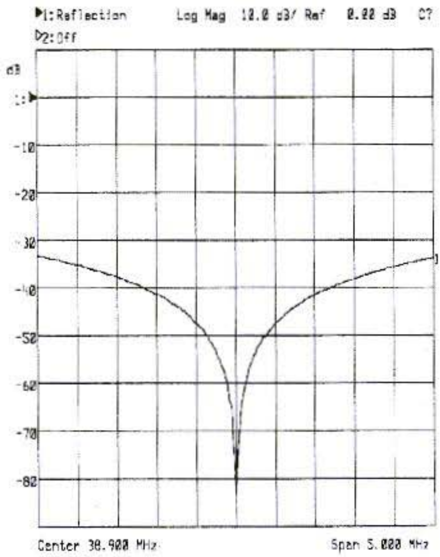


Fig. 5: Reflection attenuation at input of 3-dB 90° distributor

appears at the total output at approximately 60 dBm, conditioned by the couplings and asymmetries of the mixer and the peripheral circuit. In accordance with the laws of vector addition, we can make the vector to disappear completely, by a suitable adjustment of $P1$ and $P2$ (more and more fascinating!).

The modulation signals, I(t) and Q(t), (up to approximately 10 MHz) find their way to the mixer inputs through 18-dB attenuators ($R4$, $R5$, $R6$ or $R14$, $R15$, 16). They are AC coupled through $C3$, $C4$ or $C6$, $C7$. The lower limiting frequency is approximately 20 kHz. If we now apply 2 Vss (sinusoidal) either to the I input or the Q input, we obtain two sidebands at the total output, each with approximately 20 dBm.

If we feed the modulation signal to both inputs simultaneously, and if we use

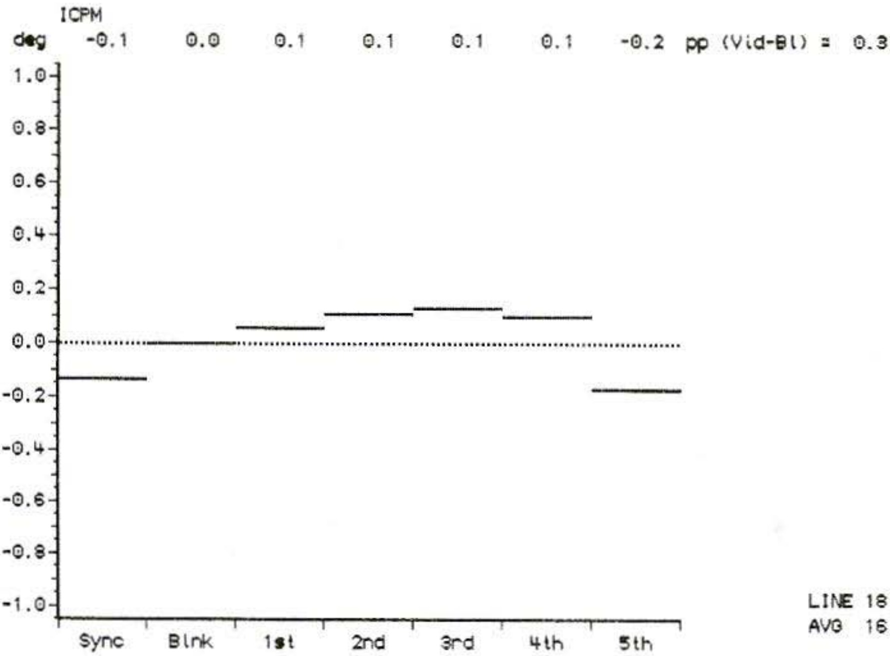


Fig. 6: I/Q modulator as ICPM-free image modulator

orthogonal signals for this, then one sideband can be strongly attenuated (theoretically obliterated). The remaining sideband is increased by 6 dB. Since the circuit is passive, the process can also be reversed. A signal (*fs*) fed into the total output generates two orthogonal signals with *fo* - *fs* at the *I* and *Q* inputs (after subsequent low-pass filtration). If *fo* > *fs*, then the *Q* signal will take precedence. If *fs* > *fo*, it is the other way round. Single-sideband technology has been making use of the options arising from this (including the combination possibilities) for decades.

As regards data transmission, since the modulator operates in a very linear manner, the *I* and *Q* modulation signals can be reliably divided into ten or more equal stages in the range between 1 V and + 1 V (whether we can also actually make use of this relatively fine quantisation depends on other conditions see above). The filtration of the modulation signals required for band limitation can take place in the basis band, on the basis of the given linearity. Initially, no static voltages are transmitted (no DC cou-

pling). We shall come back to this.

Parts list:

1 x 27 Ohms, 1%, *R*8

4 x 75 Ohms, 1%, *R*10, *R*17, *R*18, *R*19

4 x 100 Ohms, 1%, *R*4, *R*6, *R*14, *R*16

2 x 270 Ohms, 1%, *R*5, *R*15

1 x 330 Ohms, 5%, 1/3 W, *R*20

2 x 390 Ohms, 1%, *R*7, *R*9

4 x 1.8 kOhms, 5%, *R*1, *R*2, *R*11, *R*12

2 x 7.5 kOhms, 5%, *R*3, *R*13

2 x 2 kOhms, spindle trimmer, *P*1, *P*2

2 x HPF 505 (mini-circuits), *RM*1, *RM*2

Or similar, VHF mixer

1 x 56 pF (if applicable, trimmer), *C*1

6 x 100 nF, ceramic, *C*2 to *C*7

1 x 47 µF, electrolytic capacitor, *C*8

1 x 0.3 µH, 11 winding on 4-mm. core, *L*1

Vogt kit with balancing core

1 x ZPD 6V2, Zener diode, *D*1

5. AN EXCURSION INTO VIDEO TECHNOLOGY

Video signals can be converted into the intermediate-frequency plane with the I/Q modulator shown here. The following circuit change is required for negative modulation (e.g. standard B/G). *R*3 changes from 7.5 kOhms to 1.5 kOhms, *C*3 and *C*4 remain short-circuited, *R*1 is removed.

The 90° coupler (*L*1, *C*1) is tuned to 38.9 MHz. The video signal must be aquired at the black level (0 V), and comes to the *I* input. With *P*1, the residual carrier can be set as desired. With a 10% residual carrier, the synchronous level at the total output is approximately 14 dBm.

What are the *Q* channel and *P*2 for? Well, because of inter-carrier sound demodulation, the modulator may give off only a flawless *I* signal. Any *Q* remains (and there are always some) cause a phase modulation of the image carrier. The I/Q modulator compensates for this, by generating an inverse *Q* carrier (DC voltage at *RM*2).

Professional television test demodulators can measure the image carrier phase modification (ICPM). Fig. 6 shows the precision of measurement to be described as perfect . It should be pointed out that the tuning of the 90° coupler is not critical in this application case. The compensation is outstandingly temperature-stable. We just have to pay careful attention to the DC voltages.

6. SIMULATION OF A MULTI-VALENT DATA TRANSMISSION

In this experiment, the *I* and *Q* channels are to be loaded with data. For simulation purposes, non-synchronous, stepped video signals are fed into the modulator

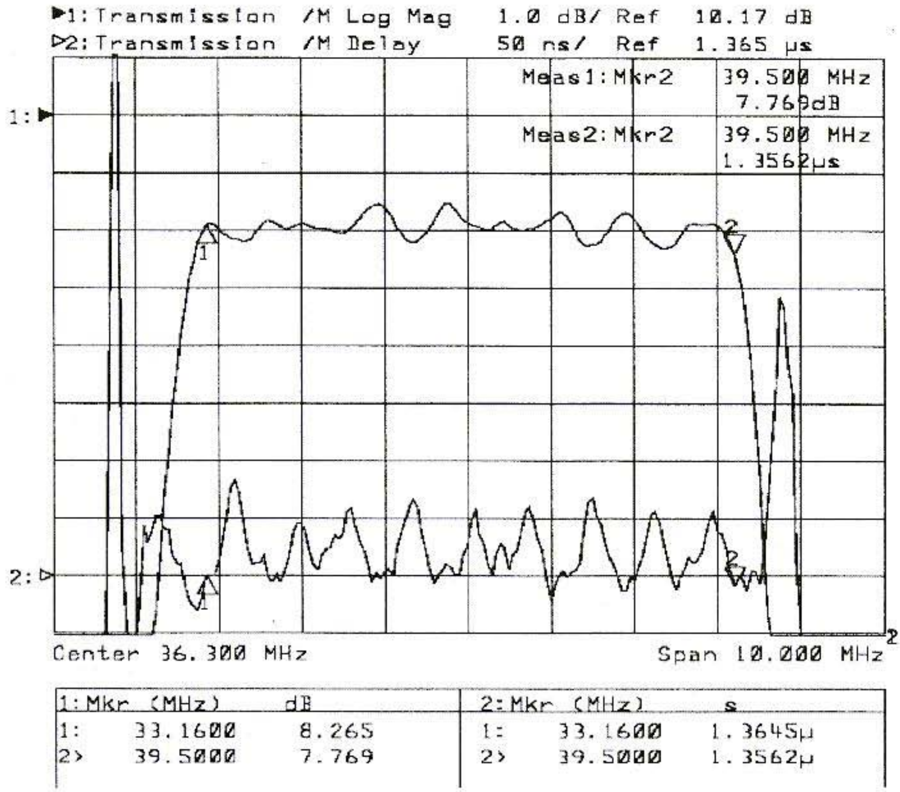


Fig. 7: Transmission curve and group delay of filter

inputs (DC coupling). The stages correspond to the voltage values 0.3 V, 0 V, + 0.14 V, + 0.28 V, + 0.42 V, + 0.56 V and + 0.7 V. Considered vectorially, this gives at least 49 possible combinations, of which only the first quadrant is completely occupied.

The I/Q modulator is driven by DC coupling i.e. *C*3, *C*4, *C*6 and *C*7 are short-circuited. An external voltage source is dispensed with (if the position of the zero point in the receiver were critical, a bipolar adjustable DC voltage would have to be fed to the mixers through *R*3 and *R*13).

An advantageously priced residual sideband filter, with pre-amplification and post-amplification, forms the transmission channel. Its transmission curve (approximately 0.7 dBpp) and group delay (approximately 50 nspp) are logged in Fig. 7. So that the modulator signal matches into the filter, the oscillator frequency is pushed into the centre of the band (here: 36.3 MHz). *L*1 and *C*1 are carefully balanced.

Now we still need a suitable demodulator. The author used a circuit with the same structure as that in the modulator (Fig. 4 suggests this). The oscillator

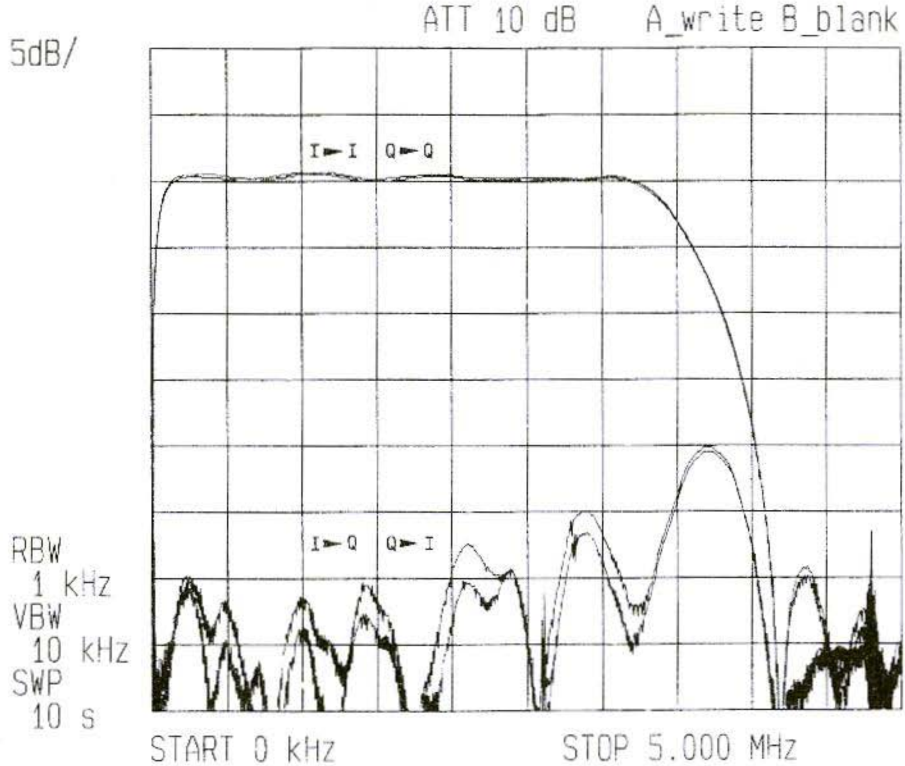


Fig. 8: Transmission curves IS → IE and / or QS → QE and cross-talk IS QE → IE

signals for the modulator and demodulator came from the same source. One of the branches was phase-adjustable, using a variable-length line (a so-called trombone).

The amplitude cycle of the total system consisting of the modulator, the filter and the demodulator was tested first (Fig. 8). The transmission curves *I*S → *I*E and *Q*S → *Q*E are quasi-identical the transmission range goes up to approximately 3.5 MHz. The cross-talk attenuation levels, *I*S → *Q*E and *Q*S → *I*E are extremely similar (more than 25 dB to approximately 3 MHz).

The demodulated signals can be looked at with the oscilloscope after low-pass filtration with $f_g \approx 20$ MHz. Fig. 9 shows both channels (the photo quality is unfortunately not optimal). The DC voltage values are correctly transmitted, i.e. the black value remains at 0 V. However, the channel cross-talk expands the original clear contours. An x-y representation is very informative. Since the modulation signals, in terms of time, move over each other, new *I-Q* combinations are arising all the time. Some of these random constellations are shown in Fig. 10. From the purely qualitative

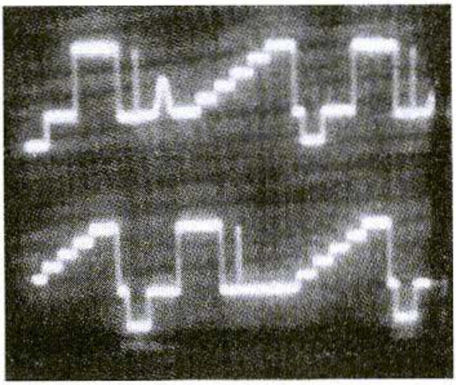


Fig. 9: Oscilloscope trace of demodulated signals

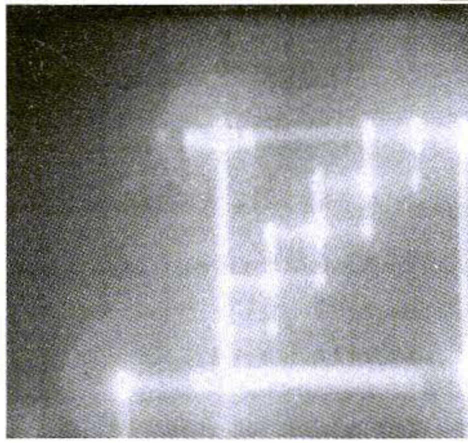


Fig. 10: X-y representation of demodulated signals

point of view, it can be stated that there should be no great difficulty in finding a reliable answer to the question of exactly what complex numerical value is being transmitted at any moment.

7. CONCLUSION

The transmission of digital data in the high-frequency plane is a new challenge for high-frequency technology. The I/Q modulator often forms the interface between digital and analogue technology. This article is intended to awake an understanding of the problems involved and to provide stimulation for further observations and experiments.

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